THE USE OF TRACERS TO TRACK THE EVOLUTION OF TOTAL WATER IN CIRRUS DURING CRYSTAL-FACE

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Introduction

Clouds play an important role in regulating the climate system through both radiative processes and by influencing the water vapor mixing ratio of the upper troposphere (UT). In order to understand how chemical and radiative changes in the boundary layer will affect the climate system it is necessary to be able to predict how changes in convective intensity will affect the amount of water vapor deposited in the UT by convective systems. To do this it is necessary to understand what physical and microphysical conditions help to determine the evolution of total water in cirrus anvils. A simple mixing model has been developed to study the mixing history of cirrus blowoff from convective anvils and to look at the evolution of total water during the lifetime of a convective event. Our model is based on the premise that in the region and time frame of interest tracers follow simple mixing relationships.

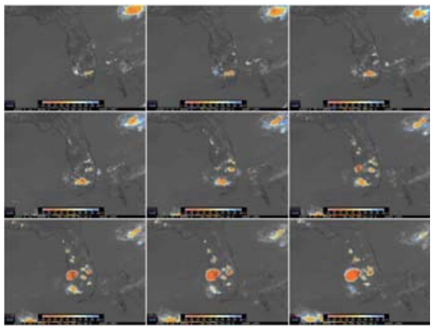

Figure 1: GOES-8 satellite images from the flight of July 16th, 2002. The convective system that was investigated forms over the southern tip of Florida and then slowly drifts southwest, where it finally dissipates. The WB-57 made several passes through this convective system between the hours of 2030 and 2300 UT, and provides a good opportunity to study the evolution of a convective system.

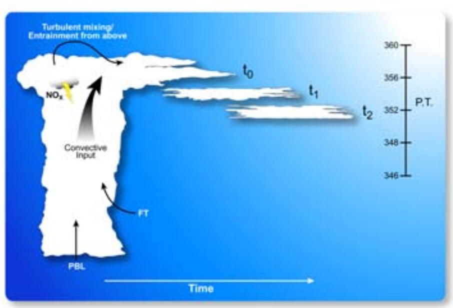

Figure 2: Schematic of convective mixing in the UT. t_0: Initially a cumulus cloud forms which entrains air and moisture from the planetary boundary layer (PBL) and the lower free troposphere (FT). In the cloud lightning can generate large concentrations of NO_x, thus elevating NO_y above its FT value. This mixture is convected upwards until it reaches the top of the troposphere. The cloud starts to spread out forming an anvil and causing turbulent mixing which entrains air from above the cloud top. t_1: The cirrus blowoff from this anvil slowly sinks and mixes with ambient air. t_2: The cirrus continues to sink and mix with ambient air eventually dissipating through sedimentation and evaporation.

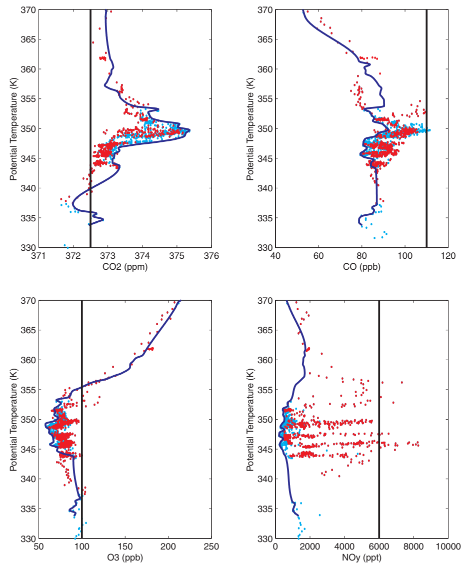

Figure 3: Ambient and convective profiles from the flight of July 16th, 2002 for CO_2, CO, O_3, and NO_y used in the model. The blue line represents the ambient profile. While we do not have measurements of the air parcel in the absence of convection, air far removed from the cloud will have undergone the least amount of mixing with the cloud air. The black line represents the value of the convective input. It is calculated based on *in situ* measurements made in the lower FT during descent. The cyan dots are measurements made in clear air around the cloud and the red dots are measurements made in the cloud.

Model Description

Assumptions:

- Tracer concentrations from the convective outflow are determined by the mixing of PBL and FT air and in the case of NO_y by lightning.
- The air in and around the cirrus outflow is made up of convective air, air entrained from above the cloud by turbulent mixing, and ambient air at the level of the cloud.
- Clear air and cloud air mix in a linear fashion.
- With the exception of NO_y, the tracers used do not depend on the amount of ice within the cloud.
- Air furthest from the cloud contains the smallest component of convective air and therefore gives the most reasonable values for "preconvective" air.

Model Equations:

- The model uses a constrained least squares fitting algorithm to minimize the equation:

$$C \cdot x - P = 0$$

- *C* is a matrix who's columns are the mixing ratios of the convective air and the ambient air at different levels (the vertical profile is divided into 2K PT bins)
- *x* is a vector containing the fractions of air from each component
- *P* is a vector containing the mixing ratio of the tracers as measured by the WB-57.

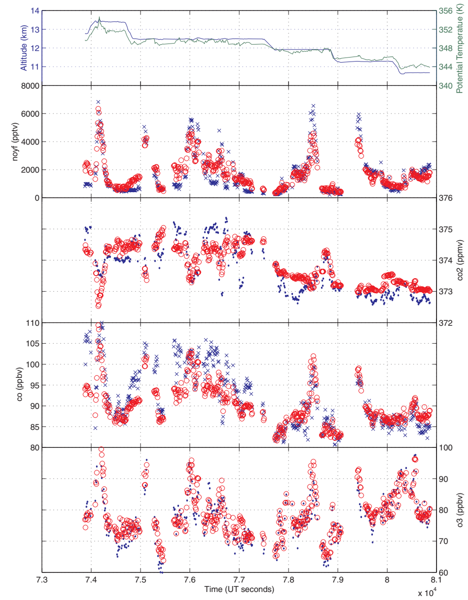

Figure 4: The top plot show the altitude of the plane (blue line) and the potential temperature of the parcel (green line). The lower four plots show the measured data (blue dots) and the model fit to the data (red circles).

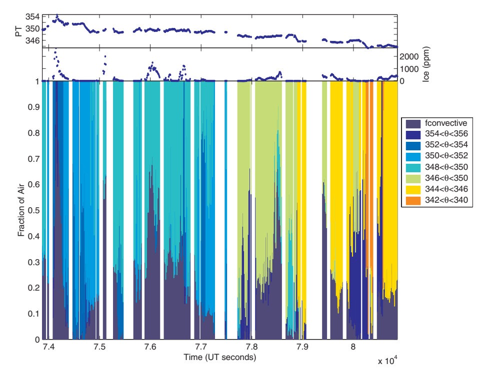

Figure 5: Top plot shows the potential temperature of the air parcel verses time in UT seconds. The middle plot shows ice measured using the Harvard total water and water vapor instruments. The bottom plot shows the fractions of different air that make up each air parcel sampled by the WB-57 according to the model. The dark blue represents the fraction of convective air in the parcel, the lighter blue through brown represents the fraction of air from different potential temperature levels as shown in the legend.

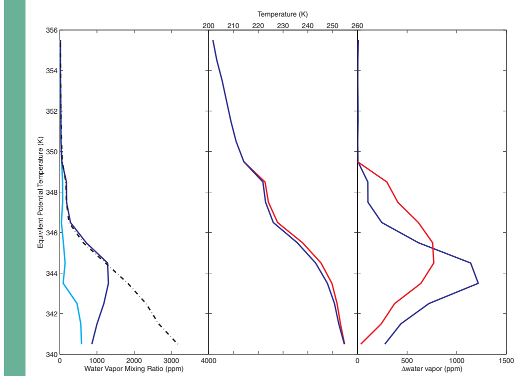

Figure 6: The left most plot shows the water vapor profile before the convection (cyan line), and after the convective event (blue line). The saturation mixing ratio is also shown (dashed black line). The data is plotted verses equivalent potential temperature. The middle plot shows the temperature profile of the parcel as measured by the WB-57 (blue line). Also plotted is what the temperature profile should look like if the parcel was following the moist adiabatic lapse rate (red line). The temperature difference between the two should result from the Latent heat of Sublimation caused by the sublimation of water vapor from ice particles. Plotted in the right most plot is the actual measured water vapor difference, Δwater (blue line), and the amount of water vapor calculated from the temperature difference between the moist lapse rate and the actual lapse rate of the parcel (red line).

Conclusions

- Using a linear combination of ambient and convective air, we successfully model the change in tracer mixing ratios in and around the cloud.
- There are regions where mixtures of air masses complicate the accurate quantification of "preconvective" ambient air.
- In order for the model to produce reasonable fits, the convective air must have a level of ozone consistent with approximately double that of the lower troposphere value of 56 ppb. Tracer-tracer correlations also show high ozone correlating with high NO_y, high CO, and low CO_2. This would suggest that ozone is being generated in the cloud, consistent with studies that have shown that the increased NO_x from lightning along with entrained ozone precursors from urban air can produce ozone plums.
- The model shows that there is vertical mixing that brings air from above the cloud top down into the cloud region.
- As the cloud descends a larger fraction of the cloud air is made up of ambient air.
- In the region above 12.5 km the ice brought up by the convective system sediments out of the air parcel and does not appreciably increase the water vapor concentration of the atmosphere.
- In the region between 9.5 and 12.5 km, a considerable fraction of the ice evaporates and saturates this region of the atmosphere.
- Using the temperature difference between the parcel lapse rate and the moist adiabatic lapse rate, a Δwater value can be calculated that agrees reasonably well with the observed addition of water.